Ninth Canadian Conference on
Earthquake Engineering
Ottawa, Ontario, Canada
26-29 June 2007

STUDY ON BRICK MASONRY INFILL WALLS WITH AIR GAP

S. Suriya Prakash[1] and P. Alagusundaramoorthy[2]

ABSTRACT

Masonry infill walls which are used as exterior or interior partitions in a reinforced concrete and steel framed structure substantially increase the strength and stiffness of the bounding frame. The strength and stiffness contribution from infill to the frame mainly depends on the interface conditions. Exact fit between the top of infill and the frame is rarely achieved thereby leading to formation of air gap. This formation of air gap is due to the fact that the frame skeleton is constructed first and then the infill. This air gap or initial gap is also increased due to shrinkage of the infill wall. The effect of air gap on the load resistance and failure mode of the infill walls is explored using experimental and finite element analysis in this study. Masonry infill wall specimens are constructed with and without air gap and tested under static loadings. Finite element model of infill walls are developed and validated with the experimental data. The validated finite element model is used to study the effect of different air gaps at the top between the frame and infill wall on the load resistance and stiffness. Based on the results, it is concluded that the ultimate load resistance and stiffness of infill walls are reduced due to the presence of air gap and the failure mode changes from ductile bed joint sliding to brittle diagonal shear cracking.

Introduction

Considerable amount of research on the behavior of masonry structures under seismic actions have been carried out all around the world. Research on masonry infilled frames has also gained importance in the recent years. Masonry infill walls are commonly used as exterior and interior partitions in reinforced concrete and steel framed structures. The masonry infills are considered as secondary and non-structural elements which add additional weight to the structural system but do not contribute to the vertical load bearing capacity. However, when the structure is subjected to seismic loads the role of masonry infill on the load resistance depends on the connection between the frame and infill. Ignoring the presence of infills is a common design practice. These infill walls increase the strength and stiffness of the bounding frames considerably (Smith 1966, Mehrabi, 1996, Buonopane and White 1999, Alchaar et al. 2002, Asteris, 2003). Recent research has also focused on using the masonry infills for the energy dissipation under strong earthquakes through seismic infill wall isolator system (Aliarri, 2005). Thus, the masonry infilled frames could be an effective and efficient method for bracing buildings against wind and seismic loading. Even though, it is beneficial under the action of wind loads and minor earthquakes, the load resistance of the infill walls is also found to damage the wall or frame under strong earthquakes. If the masonry infills are damaged before the development of large shear forces, which might possibly damage the main structural system, they dissipate seismic energy and prevent large deformations of the frames as well as

---

[1] GRA, Department of Civil Engineering, University of Missouri Rolla, Rolla, Missouri, USA
[2] Associate Professor, Strucutral Engineering Division, Indian Insitute of Technology Madras, Chennai, India

the damage that would occur to other non structural elements as a result of excessive deformations (Tomazevic, 1999). The influence of masonry infill on the basic structural frame system is manifold and in order to make the design guidelines simple, most of the codal provisions do not take into consideration the load carrying capacity of the infill wall in the design of infilled frames (Example, IS 456:2000). These infill walls could also change the failure mode of the frame if considered as a part of the frame. Therefore, the real strength of these infilled frame structures and their ability to withstand moderate and large earthquakes must be evaluated in a detailed manner. On the other hand, neglecting the contribution of infill wall by complete isolation of infill walls from frames by separation gaps leads to poor fire and acoustic protection. Furthermore, the separation gaps may also reduce the out-of-plane stability of the infill wall.

The design approach for the infilled frame system should be clear in including the infill wall as a part of load resisting structural system (Eldakhakhni 2002). Adequate detailing has to be provided to achieve the ductile behaviour of infill wall by ensuring good connection between the masonry infill wall and the frame if the infill wall is considered as a load resisting part of the frame system. The contribution of infill wall to the frame stiffness mainly depends on the interface connection between the infill wall and the frame and it should be taken in to account while designing. Based on the connections at the interface, infilled frames can be classified into two types. An infilled frame system without connectors or strong bonding at the interface is called a non- integral frame and an infilled frame with shear connectors or strong bonding at the interface is called an integral infilled frame. In normal construction practice, the frame is constructed first and then the infill walls. During this process an exact fit or strong bonding may not be achieved at the interface between the frame and the infill wall at the top of the infill wall. This air gap or initial gap is also increased due to shrinkage of the infill wall. Only very limited information is available on the effect of air gap on the behaviour of infill walls (Riddington, 1984). The effect of air gap on the seismic behaviour of infill walls has not yet been studied considering its importance and the report of numbeof failures of infill walls in the past earthquakes. In the present study, specimens were tested with different air gaps namely 0 mm, 10 mm, 20 mm at the top between the infill wall and frame. The test results of specimens with and without air gap are analysed with respect to decrease in load resistance, stiffness and failure mode. In order to understand the effect of different air gaps as a parametric study, finite element models of infill walls with air gap are developed and validated with experimental data. The effect of air gap is studied by introducing a gap between the frame and the infill wall at the top of infill wall. The experimental and finite element results are compared and discussed.

Literature Review

Early research work on infill walls was reported by Poylakov (1952). The author found that the infill walls significantly increased the load resistance of the frame. Later, Holmes (1961) suggested the concept of equivalent diagonal strut for the analysis of infilled frames and that was further used and modified by many researchers namely Smith (1966), Mainstone (1971) and Saneinjad and Hobbs (1995). Equivalent diagonal strut approach is commonly used even today by the researchers to predict the strength and stiffness of the infilled frames. The concept of equivalent diagonal strut approach in which the infill as a whole was replaced by a non-linear diagonal spring, was also proposed by Seah (1998). The author suggested a simple force-deformation response for the equivalent diagonal spring which could be used for the analysis of infilled frames. Later, single strut approach was refined to three strut approach by El-Dakhakhni (2002) for estimating the stiffness and the in-plane capacity of concrete masonry-infilled steel frames. In this method, each masonry panel was replaced by three struts with force-deformation characteristics based on the orthotropic behavior of the masonry infill wall. Though the methods suggested by above researchers are simple and effective to use, the effect of interface properties were overlooked by them in their study. Riddington (1984) was the first one to study the influence of initial air gap on the behavior of infilled frame behavior through full scale testing of six block work filled steel frames and also using finite element method. The author simulated the experimental results using interface joint elements and studied the effect of initial air gap on relatively flexible and stiff frame. The author concluded that even small amount of initial air gap reduced the stiffness of the frame considerably and the corners of the infill wall must be designed to prevent local crushing failure. The effect of connecting the infill to the frame was studied by Achyutha et al (1986). The effects of size of opening and different types of stiffeners at the interface on the lateral stiffness of the frame and on the stress distribution in the infill were reported by the above authors.

Performance of the infill walls in the past earthquakes confirms that they are very vulnerable and damage to these walls resulted in loss of human lives and damage to property irrespective of they being integral or non integral. During the strong earthquake events, infill walls have also resulted in the softy story mechanism or short column mechanisms leading to total failure of the building system. Number of such failures has also been reported in the recent earthquakes like Killari and Bhuj in India (Figure 1). The analysis of these earthquake damage and mechanisms of collapse have provided the basis for the development of methods for structural verification of newly designed buildings. Though there are number of studies reported on the infilled frames, still there is no clear consensus among the designers regarding the design of infilled frames. Review of literature clearly indicated that experimental and analytical study is further needed to understand the influence of air gap in the load resistance of infilled frames and their failure modes. Moreover, there is no information available in the literature on the effect of air gap on the strength and stiffness degradation of infills under seismic loading. The interface connections are very critical in achieving the desired behavior of infills during earthquakes. It is essential to investigate the effect of air gap and its impact on the behavior of infilled frame system so that measures for the future improvement could be developed. Hence, it was decided to study the effect of air gap on the load resistance and stiffness of infill walls constructed using locally available table molded bricks and cement mortar which is the construction practice in India.

(a) **(b)**

Figure 1. Failure of Buildings in Bhuj Earthquake (a) Masonry Infilled Frame and (b) Soft Story Mechanism of Failure.

Experimental Study

Experiments were conducted on three specimens with different air gaps. Infill walls with air gap of 10 mm and 20 mm were constructed and tested to estimate the reduction in load resistance and stiffness. The experimental setup for the infill walls is shown in the Fig. 2. Three masonry infill wall specimens such as BM10M, BM20M and BM20C with size of 1200 mm x 800 mm x 110 mm were constructed using cement and mortar mixed in the ratio of 1:5 and surface plastered with cement and mortar in the ratio of 1:4. In the designation of specimens, BM represents the brick masonry, the number 10 or 20 refers to the amount of air gap and M represents monotonic and C represents the cyclic loading. The specimens BM10M and BM20M were tested under static monotonic loading and the specimen BM20C was tested under static cyclic loading. Details of the experimental study can be found elsewhere (Suriya Prakash 2005). The test result of infill wall without air gap is taken from another experimental study (Ramesh 2003) for comparing the behavior of infill walls with air gap. The material properties of brick masonry were obtained from the testing of brick masonry wallettes of size 400 mm x 400 mm under uniaxial compression. The wallettes were made with a height to length ratio equal to one and height to thickness ratio equal to three as per IS: 1905-1987 and EN 1052:1 1998. Locally available table molded bricks of average size 220 mm x 110 mm x 70 mm were used for the construction of infill walls. The average compressive strength of bricks under compression normal and parallel to bed joint was respectively 9.6 N/mm^2 and 4.3 N/mm^2. Mortar made using cement and sand in the ratio of 1:5 for M1 grade with a minimum compressive strength of 5 N/mm^2 was used. The experimental results showed that the first cracking displacement reduced from 16 mm to 11 mm for the air gap of 10 mm and from 16 mm to 10 mm for the air gap of 20 mm. The stiffness of the infill wall also reduced by 12 % and 16 % due to air gap of 10 mm and 20 mm respectively compared to specimens with no air gap. The failure mode changed from ductile sliding to brittle diagonal cracking due to the presence of air gap (Fig. 3). The final failure of specimen under cyclic loading was due to the formation of two major diagonal cracks along the compression diagonal and tension diagonal at reduced displacement levels (Fig. 4). The ultimate load resistance decreased considerably with reduction in energy dissipation on each cycle for the specimens with air gap when compared to specimen with no air gap. The amount of energy dissipated was higher in the specimen with no air gap than in the case of specimen with air gap due to ductile bed joint sliding failure.

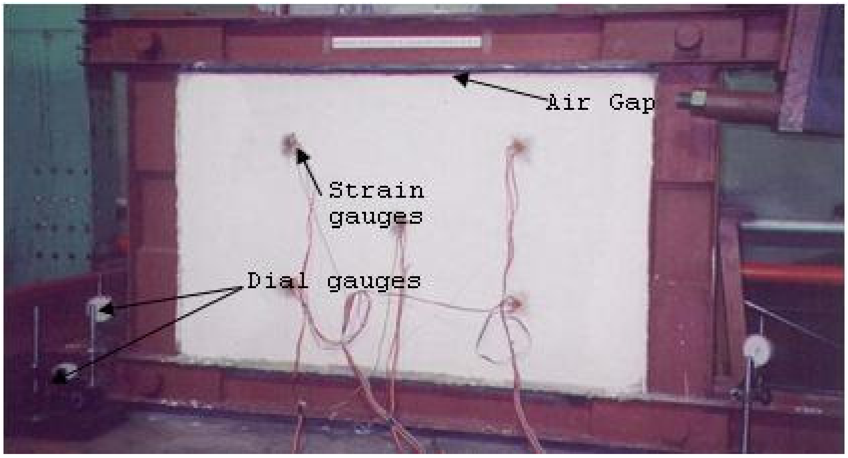


Figure 2. Experimental Setup for Infill Walls.

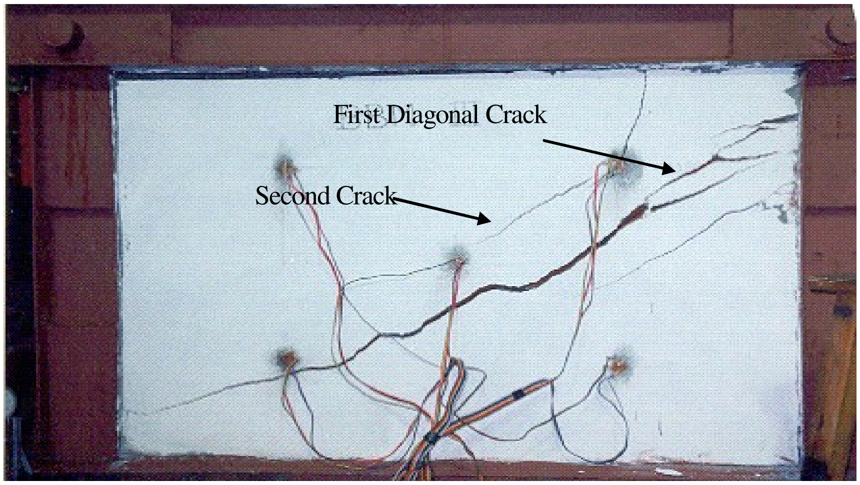


Figure 3. Failure Mode of Infill Wall with Air Gap under.

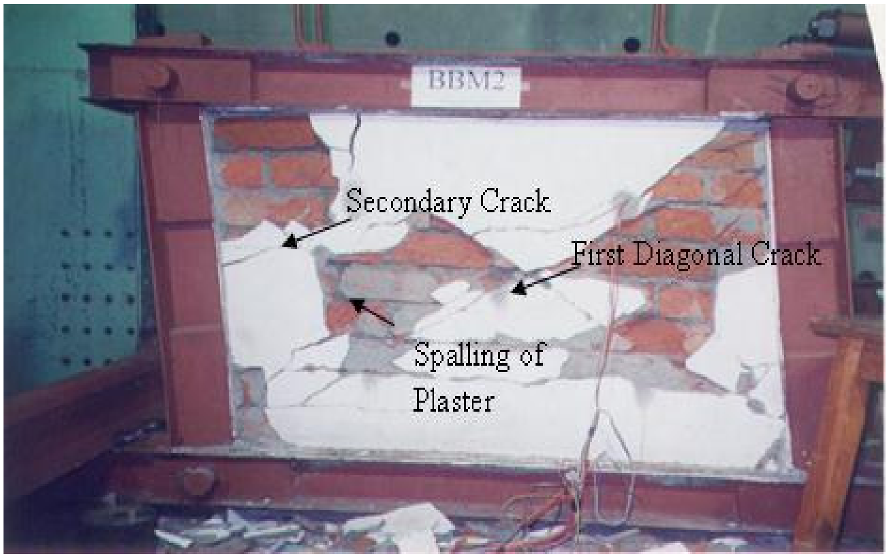


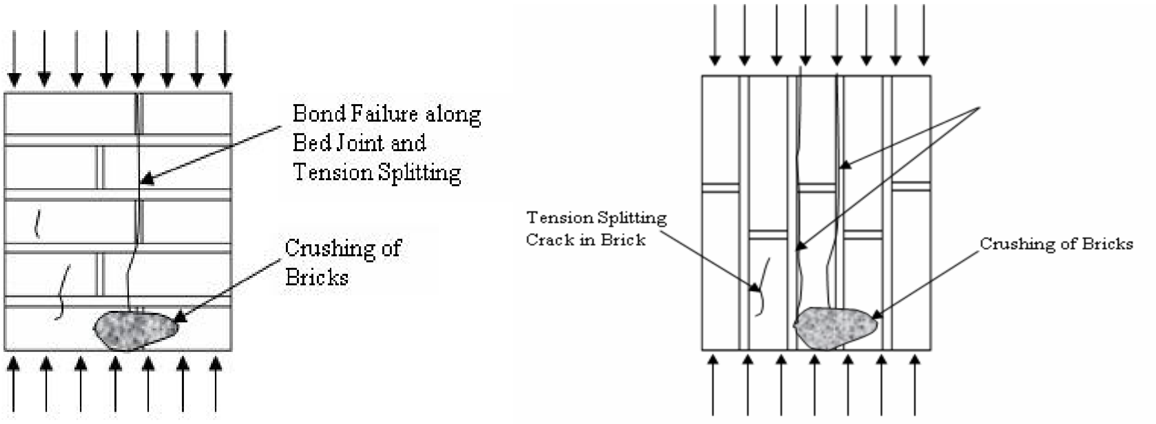
Figure 4. Failure Mode of Infill Wall with Air Gap under Cyclic Loading.

Modelling of Masonry Infill Walls

Experimental results were used to validate the finite element models. Finite element models were created and parametric studies were conducted. The effect of air gap on the load resistance of infill walls is studied using smeared crack concrete model employing macromodelling concepts. In macromodelling of masonry walls, brick unit, mortar and interface of brick masonry are modeled using a single equivalent continuum. The advantage of using macromodeling is reduction in computational cost and the possibility of analyzing large structures. Smeared crack concrete model (Hibbit et al. 2002) can be used to predict the behaviour under monotonic loading for brittle materials like masonry that exhibits different yield strength along compression and tension. The smeared crack concrete model requires the uniaxial stress-strain relationship for the masonry and its post cracking behaviour under tension which is defined by the "tension stiffening" option. Although tension stiffening option is inappropriate for the unreinforced masonry due to the lack of reinforcement, default values are adopted to avoid the numerical instability problems. The failure surface for the masonry was defined using the appropriate values from the test results of Andreaus (1996) and Dhanasekar et al. (1984). The behavior of finite element model was validated with experimental test data of infill walls by adjusting the default values of tension stiffening and failure surface parameters.

Material Properties

The Young's modulus for the steel frame was taken as 2.0 x 10^5 N/mm^2 and Poisson's ratio as 0.2. The infill wall was modeled using smeared crack concrete material model. The material properties of brick masonry infill wall were taken from the material characterization of bricks masonry wallettes tested under compression parallel and normal to bed joint (Figure 5) following the provisions of EN 1052-1 (1998). The modulus of elasticity of infill wall for the numerical study was obtained from material characterization as 168 N/mm^2. The nonlinear stress strain curve (stress and corresponding absolute plastic strain) were given as input parameters for smeared crack concrete model (Table 1). The Poisson's ratio for the masonry material is normally around 0.15 to 0.2 and has been taken as 0.2 for modelling.



(a) (b)

Figure 5. Failure Mode of the Wallettes under Compression (a) Loading Normal to Bed Joints and (b) Parallel to Bed Joints.

Table 1. Input Parameters for the Nonlinear Part of Macromodeling.

Compression Normal to Bed Joint		Compression Parallel to Bed Joint	
Stress (N/mm^2)	Absolute Plastic Strain	Stress (N/mm^2)	Absolute Plastic Strain
3.10	0.00000	3.10	0.00000
3.00	0.00025	2.95	0.00170
2.90	0.00050	2.51	0.00355
2.50	0.00150	2.00	0.00515
1.60	0.00350	1.61	0.00675

Discretization of Infill Wall and Steel Frame

The steel frame elements were considered to be rigid and non-deforming. They were modelled as two node rigid truss elements (T2D2) in the finite element model. The infill wall was modelled using four node plane stress elements (CPS4R). The elements T2D2 and CPS4R are available in ABAQUS standard element library. The interface between frame and infill was modelled using interface elements through master slave approach. The surface to surface contact was established between the infill wall and frame. The frame surface was considered as master surface and infill wall surface was considered as slave surface (Fig. 6). The coefficient of friction at the interface between the infill wall and the steel frame was assumed as 0.6. The air gap between the infill wall and the frame were considered and modelled using interface/gap elements. Tangential behaviour of the interface between the frame and infill wall was modelled using penalty friction approach using a friction coefficient of 0.6. The normal behaviour of the interface was modelled using linear pressure over closure with normal stiffness of 1000 N/mm.

Loading and Boundary Conditions

The frame at bottom was arrested for translations in x and y directions. The in-plane load was applied along x-direction at the top left corner of the frame as shown in Fig. 6. The in-plane lateral load in terms of displacement was increased linearly from 0 mm to 40 mm. The static linear lateral displacements were applied in increments. The analysis was carried out till the principal strains in the specimens reach the failure strain of masonry under compression or tension.

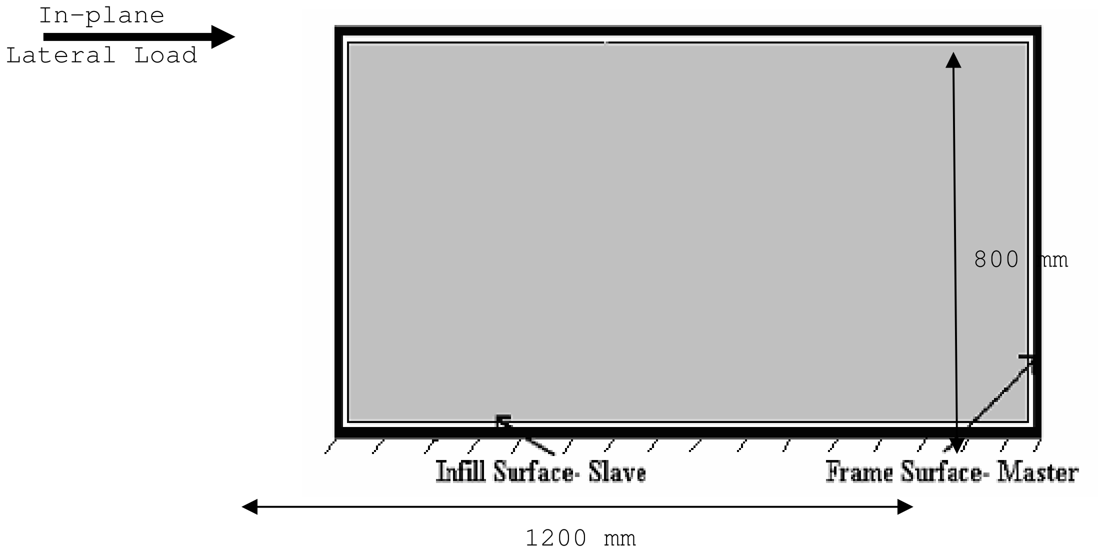


Figure 6. Surface to Surface Contact between the Frame and Infill.

Validation of Finite Element Model

The stress pattern along the diagonal showed the strut action of the infill wall in the frame (Fig. 7). The load resistance/displacement curves from the experimental and finite element study are shown in Fig. 4. The finite element result was in agreement with experimental data upto initial cracking. Thereafter, the finite element model overestimated the post cracking behavior but the ultimate load predicted was in close agreement with the experimental data (Fig. 8). The maximum load resistance from finite element model was found to be 118 kN for the infill wall without air gap compared to the experimental ultimate load of 114 kN. The effect of 10 mm (FEM 10 mm) and 20 mm (FEM 20 mm) air gap on masonry infill walls was studied numerically and compared with experimental data. The finite element model overestimated the stiffness of infill wall with air gap (Fig. 8). The predictions of the finite element model were in reasonable agreement with experimental data. There was small difference in prediction of load–displacement curve after the initial cracking but the predictions were in agreement with the experimental behavior at the ultimate.

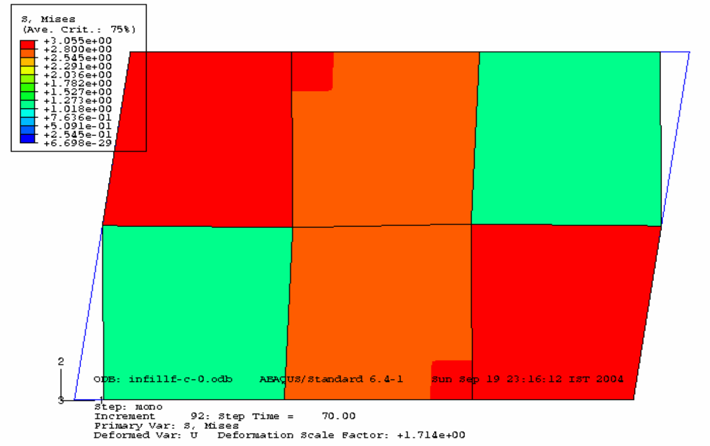


Figure 7. von Mises Stress Distribution on Infill Wall with No Air gap.

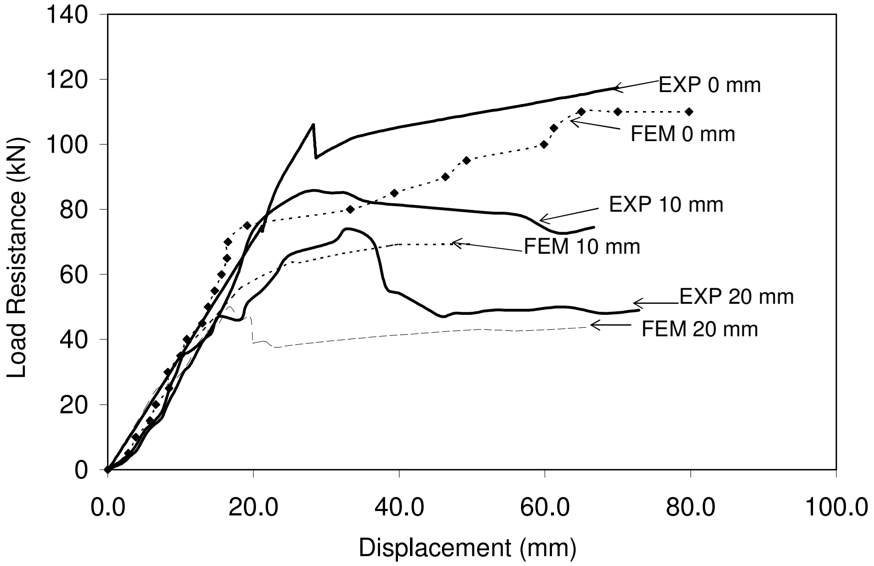


Figure 8. Load Resistance/Displacement curves of Infill Walls with Different Air gap from FEM and Experimental Study.

Results and Discussion

As a parametric study, the effect of different air gaps namely 0 mm, 5 mm, 10 mm, 15 mm and 20 mm were studied. The load resistance/displacement curves of infill walls with different air gap of 5 mm, 10 mm and 20 mm are shown in Fig. 9. The stiffness of infill wall increased significantly due to the contact between the frame and infill wall with increase in applied displacement in the specimen without air gap and reduced significantly when the air gap between the top beam and infill is increased from 0 mm to 20 mm. In the model with no air gap, the contact length between beam and infill wall was calculated to be one fourth of the interface length and it remained constant until the ultimate load was attained. The finite element results also proved that the contact length between the infill wall and frame increased linearly with the amount of air gap. The ultimate strength was attained when the strain at the loaded compression corner reached its failure strain and started crushing. After reaching the ultimate load, there was no significant change in the load resistance due to the friction and normal pressure developed in the contact area.

The ultimate load resistance was 114 kN for the specimen with no air gap. The first cracking displacement was 8 mm. The ultimate load resistance reduced to 80 kN, 64 kN and 52 kN respectively from 114 kN for the specimen with air gap of 5 mm, 10 mm and 20 mm respectively compared to the specimen with no air gap (Fig. 9). The cracking displacement increased for the specimens with increase in air gap. This is due to the fact that, infill wall has to move a distance equal to that of gap between the frame and top of the wall to maintain contact with the frame and start resisting the load. The results from the parametric study indicated that even the presence of small air gap in the infill wall led to a significant reduction in ultimate load resistance and considerable reduction in stiffness. There was also change in the strut formation along the diagonal compression due to the presence of initial gap. von Mises stress distribution on infill walls showed that the width of the diagonal strut reduced with increase in the air gap. Reduction in equivalent diagonal strut width due to the effect of air gap should be incorporated in the analysis of infilled frames by employing suitable reduction factors.

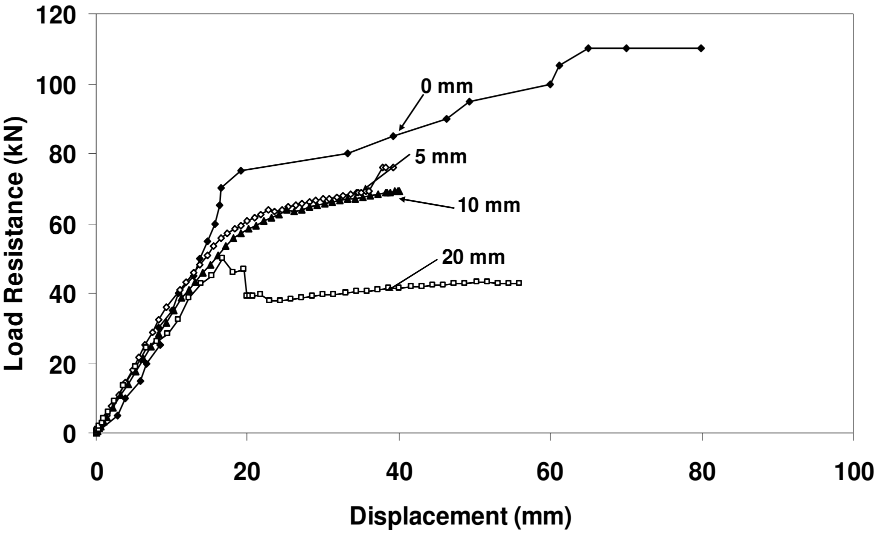


Figure 9. Load Resistance/Displacement Behaviour of the Infill Walls with Air Gap.

Summary and Conclusions

The effect of air gap on the load resistance and stiffness of the infill walls were analyzed in this study. Experiments were conducted on specimens with and without air gap. Finite element models were developed and validated with experimental data. The finite element models were found to predict the behaviour of infill walls reasonably well. After the validation of model, effects of different air gap were analyzed as a parametric study. Based on the results, following major conclusions are drawn.

i) Air gap in the infilled frame leads to a significant reduction in load resistance and considerable reduction in stiffness.
ii) There is a change in the strut formation along the diagonal compression due to air gap. von Mises stress distribution on infill walls showed that the width of the diagonal strut reduced with increase in the air gap.
iii) Reduction in equivalent diagonal strut width due to the effect of air gap should be incorporated in the analysis of infilled frames by employing suitable reduction factors during calculation of strut width in design of infilled frames.
iv) The presence of air gap leads to reduction in energy dissipation capacity of the infill.
v) The presence of air gap changes the failure mode from ductile bed joint sliding to brittle diagonal shear cracking.
vi) The air gap could also reduce the out of plane strength of infill walls and change their failure mode under earthquakes. However, this needs to be studied in detail by means experimental and finite element study.

Acknowledgements

The authors would like to thank all the staff members of the Structural Engineering Laboratory, IIT-Madras, Chennai, India for their help and assistance during the testing of the specimens.

References

Achyutha, H., R. Jagadish, P.S. Rao, and S.S. Rahman, 1986. "Finite element simulation of the elastic behaviour of infilled frames with openings", *J. Computers & Structures*, Elsevier, 23(1), 865-696.

Al-Chaar, G., M. Issa, and S. Sweeney, 2002. "Behaviour of masonry-infilled nonductile reinforced concrete frames" *J. Struct. Engng.*, ASCE, 128 (8), 1055-1063.

Aliari, M., 2005. “Development of seismic infill wall isolator subframe (SIWIS) system”, Ph.D Thesis, Department of Architectural Engineering, Pennsylvania State University, USA.

Andreaus, U., 1996. “Failure criteria for masonry panels under in-plane loading.” *J. Struct. Engng.,* ASCE, 122 (1), 37-46.

Asteris, P.G., 2003. “Lateral stiffness of infilled plane frames”, *J. Struct. Engng.,* ASCE, 129 (6),1071-1079.

Buonopane, S.G., and R.N. White, 1999. “Pseudodynamic testing of masonry infilled reinforced concrete frame.” *J. Struct. Engng.,* ASCE, 125 (6), 578-589.

Dhanasekar, M, A.W. Page, and P.W. Kleeman, 1985. “The failure of brick masonry under biaxial stresses”. *Proc. Inst. Civ. Eng.* (Part 2); 79, 295-313.

El-Dakhakhni, W.W. 2002. “Experimental and analytical evaluation of concrete masonry-infilled steel frames retrofitted using GFRP laminates.” *PhD thesis*, Drexel University.

EN 1052-1 1998. “Methods of test for masonry - Part 1: determination of compressive strength”, European Standards.

Hibbit, D., B. Karlson, and P. Sorensen, 2002. “ABAQUS/Standard theory manual”.

Holmes, M., 1961. “Steel frames with brick work and concrete infilling”, *Proc. Inst. Civ. Eng.,*London, England, Part 2, 73, 473-478.

IS: 456, 2000. “Indian standard code of practice for plain and reinforced concrete”, Bureau of Indian Standards, New Delhi.

IS: 1905, 1987. “Indian standard code of practice for structural use of unreinforced masonry”, Bureau of Indian Standards, New Delhi.

Mainstone, R.J., 1971. ‘‘On the stiffness and strength of infilled frames.’’ *Proc. Inst. Civ. Eng., Struct. Build., Suppl.,* 57–90.

Mehrabi, A.B., and Shing, P.B., 1996. “Finite element modeling of masonry-infilled RC frames.” *J. Struct. Eng.,* ASCE, 123 (5), 604-613.

Polyakov, S.V., 1952. “Masonry in framed buildings”, Gosudarstevennoe Izdatel Stvo Literatury po Stroitel Stvui Arkhitektuze, Moscow ~translation into English by G. L. Cairns.

Ramesh, P., 2003. “Retrofitting of masonry infill walls to resist earthquake loads”, *M.Tech Thesis*, Dept. Civil Eng., I.I.T Madras, Chennai, India.

Riddington, J.R., 1984. “The influence of initial lack of fit on infilled frame behaviour.” Proc. Instn. Civ. Engrs, Part 2, 1984, 77, 295-310.

Saneinajad, A., and B. Hobbs, 1995. ‘‘Inelastic design of infilled frames.’’ *J. Struct. Eng.,* 121(4), 634–650.

Seah, C.K., 1998. “A universal approach for the analysis and design of masonry infilled frame structures”, Ph.D. Thesis, University of New Brunswick, Fredericton, N.B., Canada.

Smith, S.B., 1966. “Behaviour of square infilled frames.” *Proc.ASCE,* 92 (ST1), Feb, 381-403.

Suriya Prakash, 2005. “Static behavior of masonry load bearing and infill walls retrofitted with FRP composites”, *MS-Thesis*, Dept. Civil Engg., I.I.T Madras, Chennai, India.

Tomazevic, M., 1999. “Earthquake resistant design of masonry buildings”, Imperial college press, ISBN 1-86094-066-8.